

Self-interacting Dark Matter via Right Handed Neutrino Portal

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(Ref.: arXiv:2110.00021 [hep-ph])

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भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

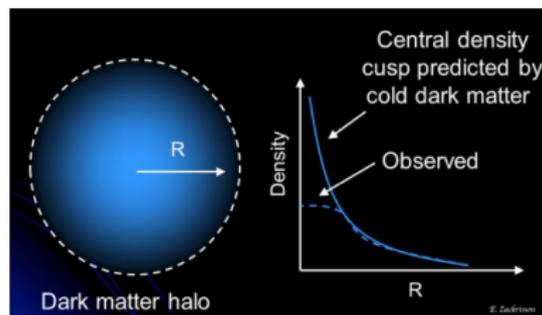
Issues with CDM

- **The cusp-core problem:**

Λ CDM: Central densities of halos \rightarrow **Cuspy**
 $(\rho \sim r^{-1})$

Observation: Central densities of halos \rightarrow
Cored ($\rho \sim r^0$).

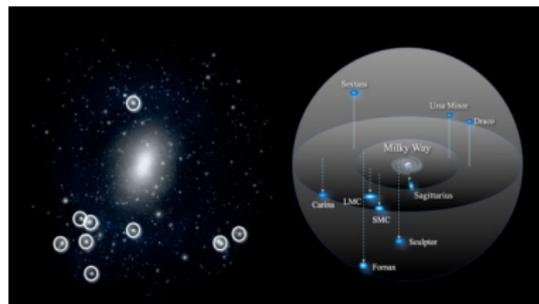
(S-H. Oh et al, Astron. J 149 180 (2015))



- **The missing satellite Problem:** Λ CDM

Simulations predict more satellites than those observed.

- **Too big to fail Problem:** Observed satellites of the MW are not massive enough to be consistent with predictions of Λ CDM.



(Weinberg, Bullock, Governato, Kuzio de Naray, Peter(2013))

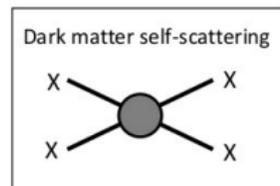
Self-interacting dark matter: a promising alternative

CDM structure problems can be resolved introducing dark matter self-interaction.

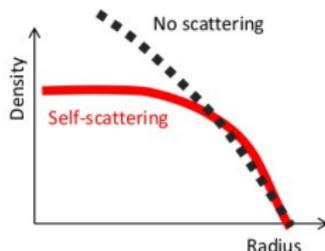
Dark matter particles in halos elastically scatter with other dark matter particles.

(D. N. Spergel and P. J. Steinhardt, *Phys. Rev. Lett.* 84 (2000) 3760–3763, arXiv:astro-ph/9909386)

SIDM: $\sigma/m \sim 1 \text{ cm}^2/\text{g} \sim 10^{-24} \text{ cm}^2/\text{GeV}$
 Typical WIMP: $\sigma/m \sim 10^{-38} \text{ cm}^2/\text{GeV}$.



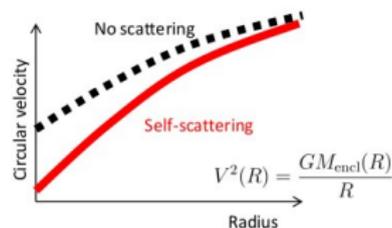
Cusp-Core Problem:



Particles get scattered out of dense halo centers.

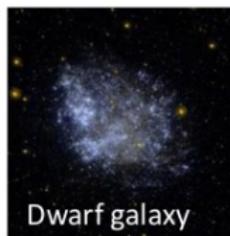
Courtesy: Sean Tulin (frascati'15)

The Missing Satellite Problem :



Rotation curves reduced (less enclosed mass)
 Simulated satellites matched to observations.

Velocity dependent self- scattering



Dwarf galaxy

Low energies ($v/c \sim 10^{-4}$)

Spiral galaxy

Medium energies ($v/c \sim 10^{-3}$)

Cluster of galaxies

High energies ($v/c \sim 10^{-2}$)

Stronger self-scattering needed for (dwarf-sized) halos.

$\sigma/m \sim 0.5 - 10 \text{ cm}^2/\text{g}$ at dwarf-scale velocity $v \sim 10 \text{ km/s}$.

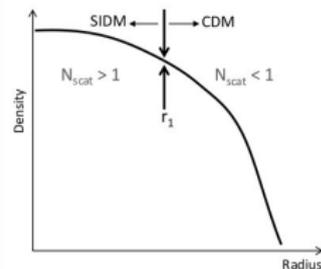
Weaker self-scattering favoured by cluster merging/halo profiles.

$\sigma/m \sim 0.1 - 1 \text{ cm}^2/\text{g}$ at cluster-scale velocity $v \sim 1000 \text{ km/s}$.

A velocity-dependent DM self-scattering.

$$\sigma \sim \frac{g^4 m_{DM}^2}{m_{mediator}^4}$$

Popular choice: a light mediator ($m_{mediator} \ll m_{DM}$) with mass 1-100 MeV.



Courtesy: Sean Tulin (frascati'15)

RHN assisted elastic SIDM and neutrino mass

Fields		$\underbrace{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y}_{\text{SM}} \otimes U(1)_D$			
Fermion	N_R	1	1	0	0
	χ	1	1	0	1
Scalars	Φ	1	1	0	-1

$$\mathcal{L}_{DM} = i \bar{\chi} \gamma^\mu (\partial_\mu - ig_D Z'_\mu) \chi - M \bar{\chi} \chi - M_{N_R} \bar{N}_R^c N_R - y \chi \Phi N_R + \frac{\epsilon}{2} B^{\alpha\beta} Y_{\alpha\beta}$$

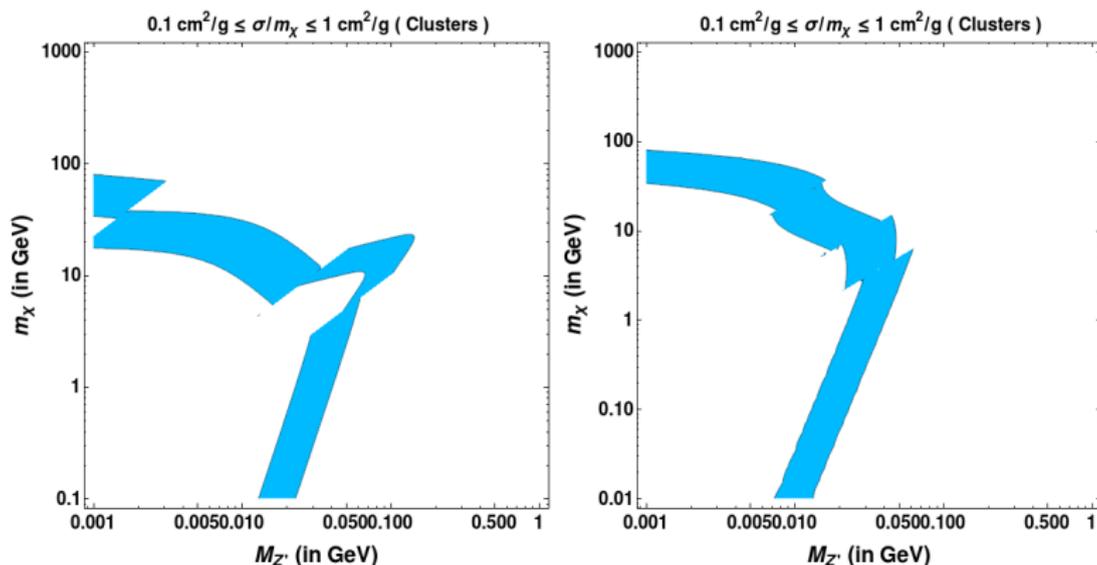
$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger (D^\mu \Phi) + m_\Phi^2 \Phi^\dagger \Phi - \lambda_\Phi (\Phi^\dagger \Phi)^2 - \lambda_{\Phi H} (\Phi^\dagger \Phi) (H^\dagger H)$$

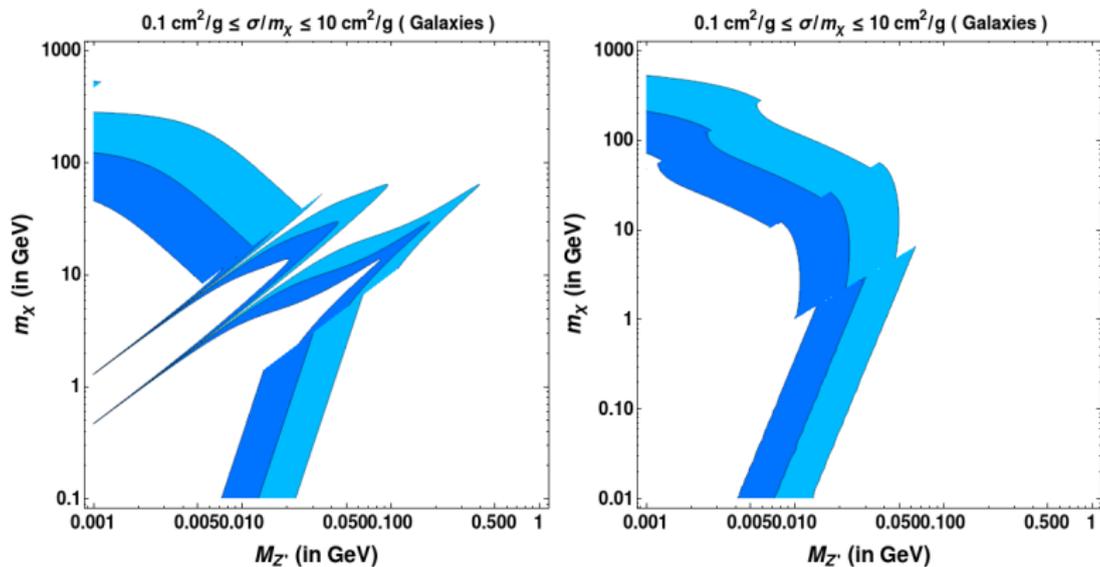
Yukawa Potential:

$$V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_{Z'} r}$$

Sean Tulin, Hai-Bo Yu and Kathryn M. Zurek

Parameter space for sufficient self-interaction





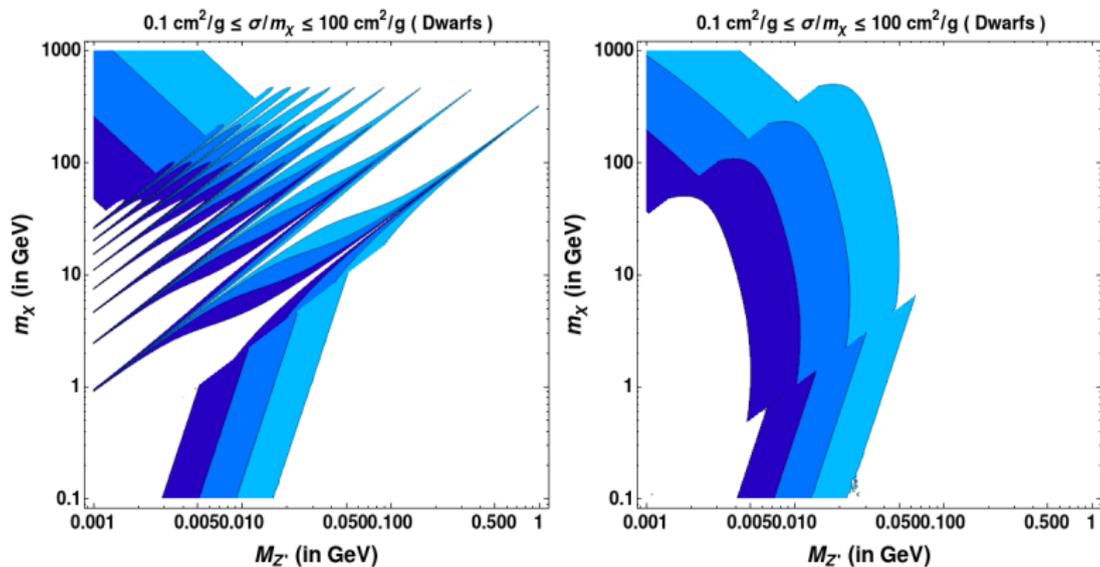


Figure: [Left]: Attractive; [Right]: Repulsive Self-interaction cross-section $0.1 - 100 \text{ cm}^2/\text{g}$ for dwarfs ($v \sim 10 \text{ km/s}$). Dark blue colour represents regions of parameter space where $10 \text{ cm}^2/\text{g} < \sigma/m_\chi < 100 \text{ cm}^2/\text{g}$; Blue colour represents regions of parameter space where $1 \text{ cm}^2/\text{g} < \sigma/m_\chi < 10 \text{ cm}^2/\text{g}$; Sky blue colour represents regions of parameter space where $0.1 \text{ cm}^2/\text{g} < \sigma/m_\chi < 1 \text{ cm}^2/\text{g}$.

Velocity dependent self-interaction

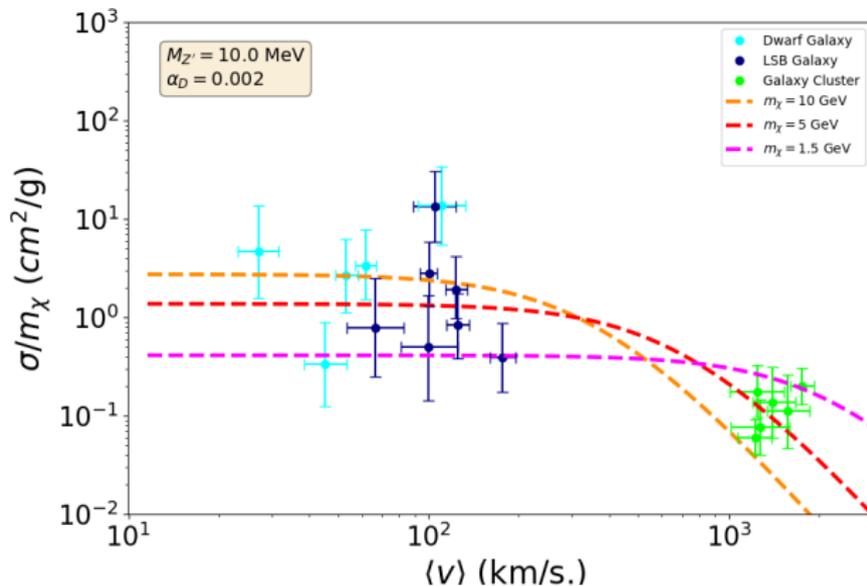
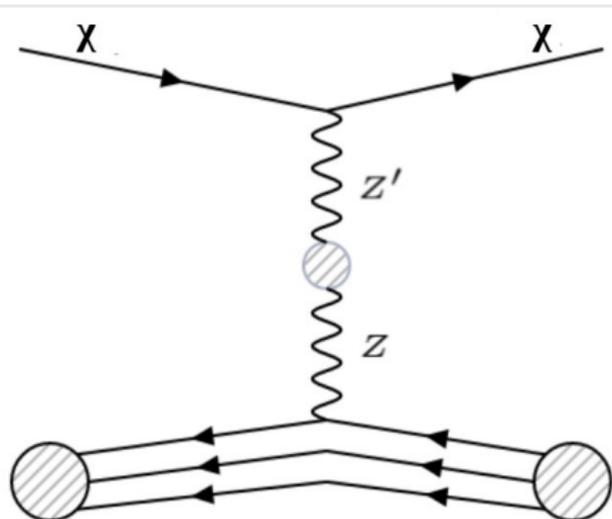
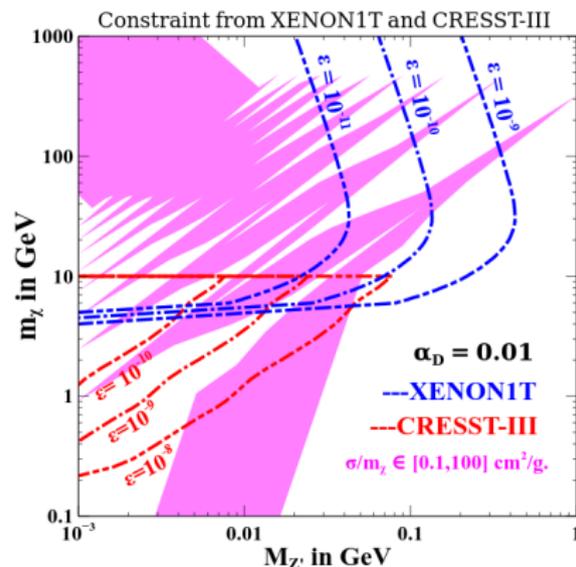


Figure: The self-interaction cross section per unit mass of DM as a function of average collision velocity.

Direct Search bound



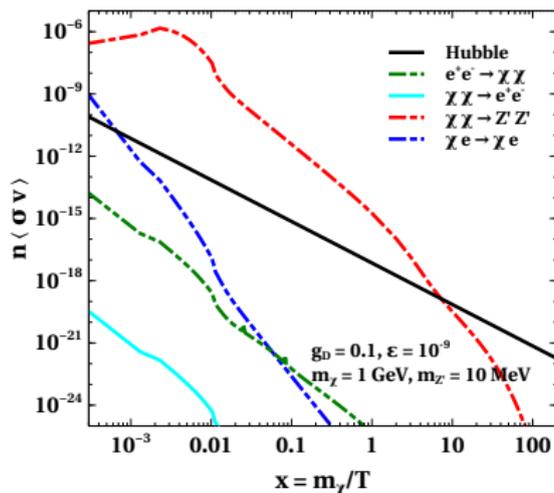
$$\sigma_{\chi N}^{\text{SI}} = \frac{g^2 g_D^2 \epsilon^2}{\pi} \frac{\mu_{\chi N}^2}{M_{Z'}^4} \frac{(Zf_p + (A-Z)f_n)^2}{A^2}$$



$$\text{However, } \Gamma_{Z'} = \frac{\alpha_{em} m_{Z'} \epsilon^2}{3}$$

$$\therefore \tau_{Z'} = 3 \text{ sec} \left(\frac{\epsilon}{10^{-10}} \right)^{-2} \left(\frac{m_{Z'}}{10 \text{ MeV}} \right)^{-1}$$

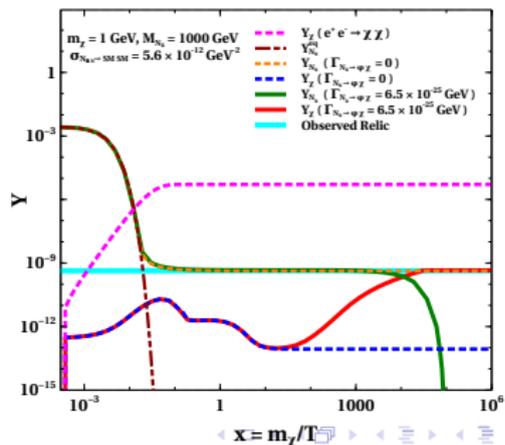
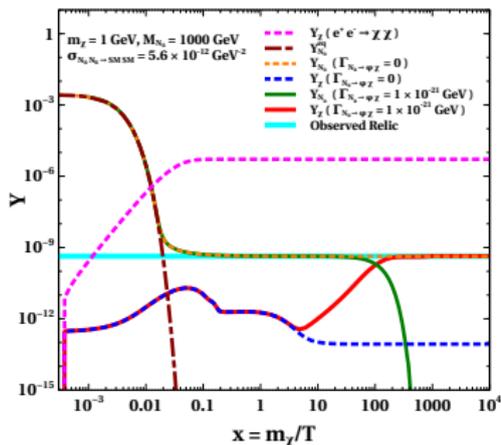
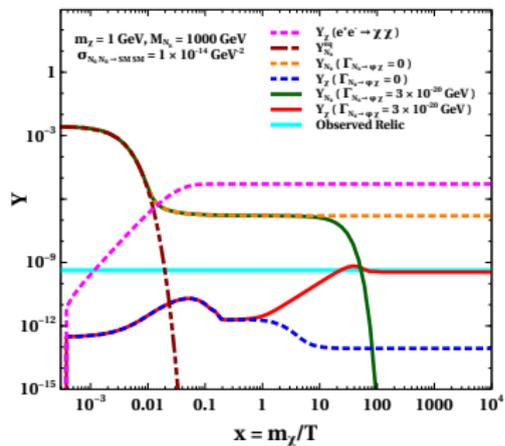
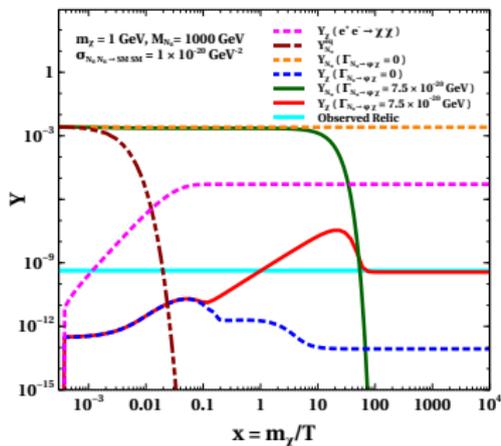
Production of dark matter



$$\frac{T'}{T} = \left(\frac{g_{*S}^{\text{SM}}(T)}{g_{*S}^{\text{SM}}(T_D)} \right)^{1/3}, \quad x' = \frac{m_\chi}{T'} = \left(\frac{T}{T'} \right) x$$

$$\frac{dY_{N_R}}{dx} = - \frac{s(m_\chi)}{x^2 H(m_\chi) \left(\frac{T'}{T} \right)} \langle \sigma(N_R N_R \rightarrow \text{SMSM}) v \rangle (Y_{N_R}^2 - (Y_{N_R}^{\text{eq}})^2) - \left(\frac{T'}{T} \right)^2 \frac{x}{H(m_\chi)} \langle \Gamma_{N_R \rightarrow \phi_\chi} \rangle Y_{N_R} \quad ;$$

$$\frac{dY_\chi}{dx} = \left(\frac{T'}{T} \right)^2 \left[\frac{s(m_\chi)}{x^2 H(m_\chi)} \left(\langle \sigma(e^+ e^- \rightarrow \chi\chi) v \rangle (Y_\chi^{\text{eq}})^2 - \langle \sigma(\chi\chi \rightarrow Z'Z') v \rangle Y_\chi^2 \right) + \frac{x \left(\frac{g_{*S}(T_D)}{g_{*S}(T_D)} \right)}{H(m_\chi)} \langle \Gamma_{N_R \rightarrow \phi_\chi} \rangle Y_{N_R} \right]$$



Relic Density: Interplay between cross-section and decay rate

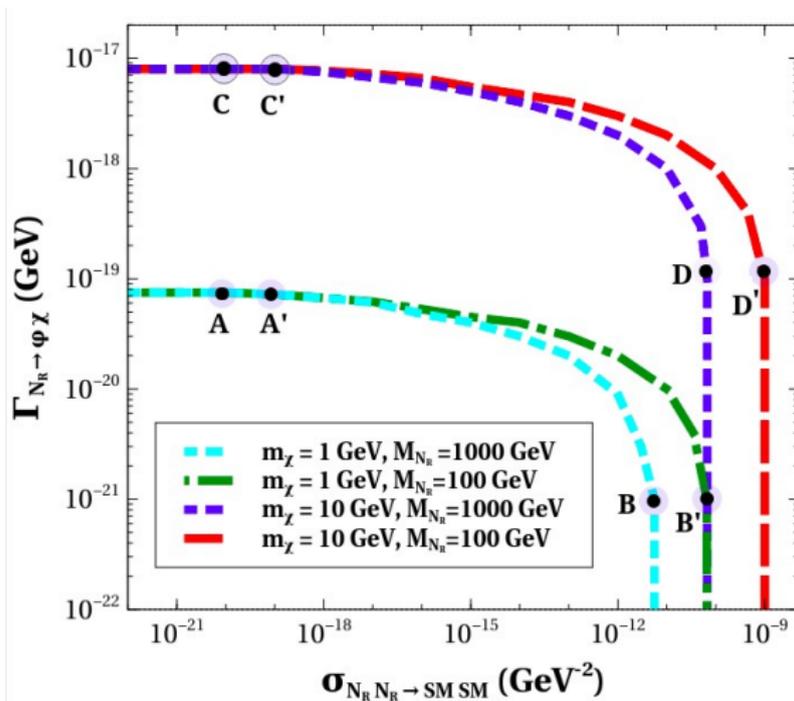


Figure: Contour of correct relic in the plane of $\sigma_{N_R N_R \rightarrow SM SM}$ versus $\Gamma_{N_R \rightarrow \phi \chi}$.

Final parameter space

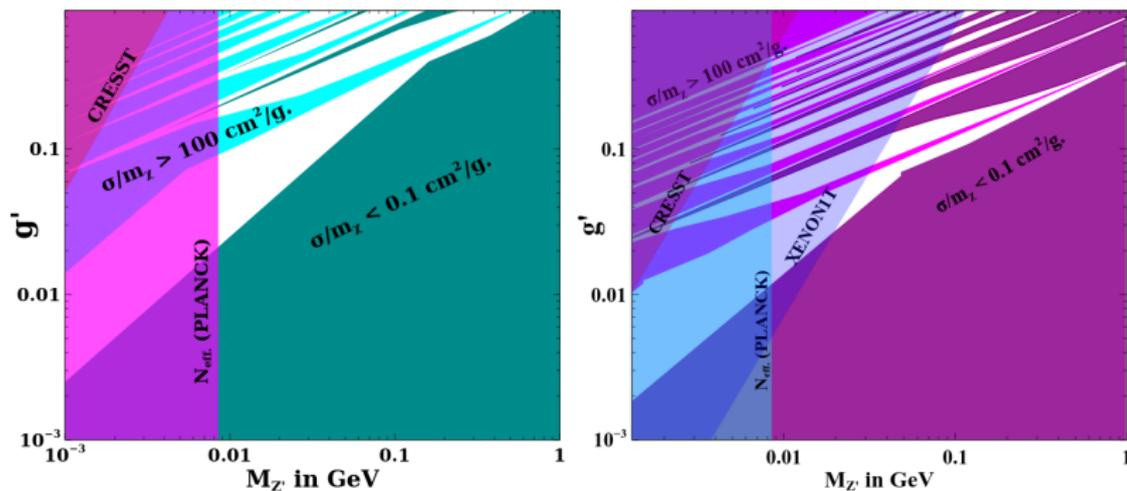


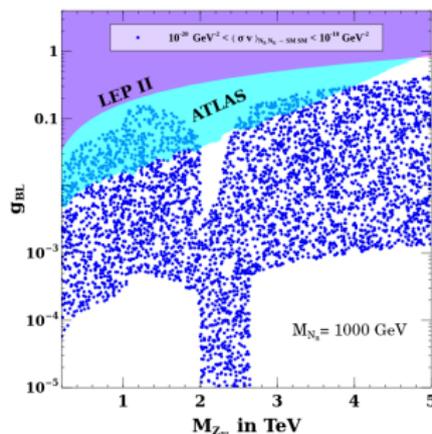
Figure: Summary plot showing the parameter space in $g' - M_{Z'}$ for $M_\chi = 1$ GeV (left) and $M_\chi = 10$ GeV (right).

Model-I: B-L model

Fields		$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{B-L} \otimes U(1)_D$
Fermion	N_R	1 1 0 -1 0
	χ	1 1 0 0 1
Scalars	Φ	1 1 0 1 -1
	ζ	1 1 0 2 0

$$\mathcal{L} \supset -\frac{1}{2} y' \zeta \overline{N_R^c} N_R - Y_\nu \overline{L} \tilde{H} N_R - y \chi \Phi N_R + \text{h.c.}$$

The light neutrino mass matrix $M_\nu = -m_D M_R^{-1} m_D^T$.

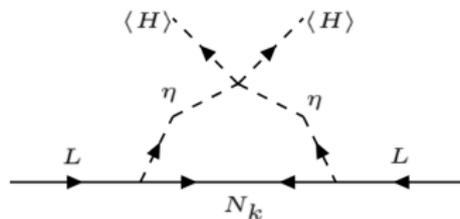


Model-II: Scotogenic model

Fields		$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_D \otimes Z_2$
Fermion	N_R	1 1 0 0 -
	χ	1 1 0 1 -
Scalars	η	1 2 1 0 -
	Φ	1 1 0 -1 +

$$\mathcal{L} \supset -\frac{1}{2} M_{N_R} \overline{N_R^c} N_R - Y_N \overline{L} \tilde{\eta} N_R + \text{h.c.}$$

$$\begin{aligned}
 V(H, \eta) = & -\mu_H^2 H^\dagger H + \frac{\lambda_H}{2} (H^\dagger H)^2 + \mu_\eta^2 \eta^\dagger \eta + \frac{\lambda_\eta}{2} (\eta^\dagger \eta)^2 \\
 & + \lambda_{H\eta} (H^\dagger H) (\eta^\dagger \eta) + \lambda'_{H\eta} (H^\dagger \eta) (\eta^\dagger H) + \frac{\lambda''_{H\eta}}{2} [(H^\dagger \eta)^2 + (\eta^\dagger H)^2]
 \end{aligned}$$



Allowed parameter space

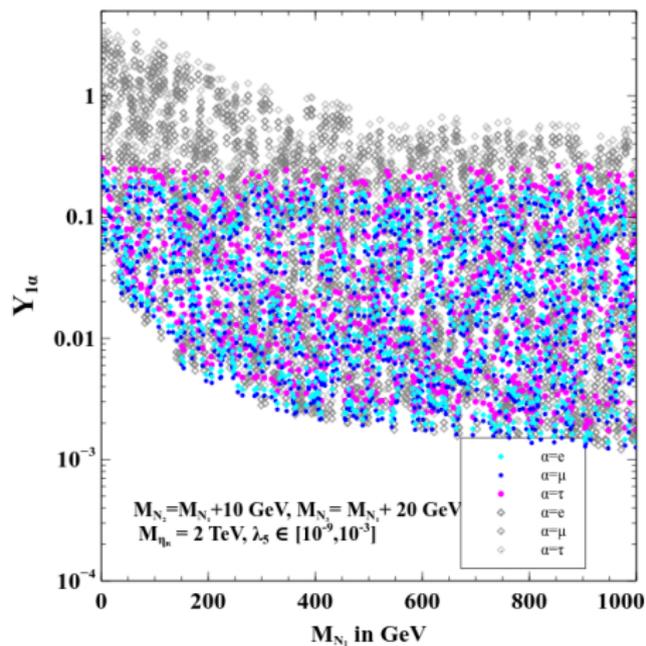
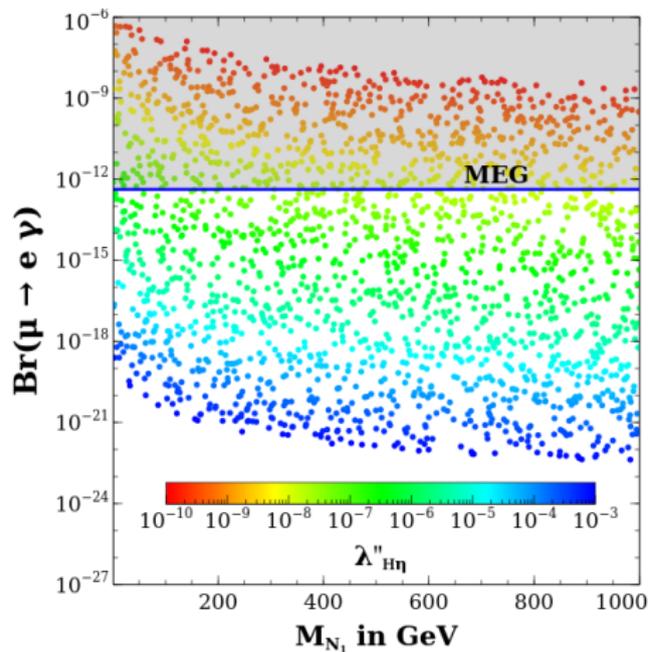


Figure: [Left]: $\text{Br}(\mu \rightarrow e \gamma)$ as a function of N_1 mass while keeping $M_{N_1} = M_{N_2} - 10$ GeV = $M_{N_3} - 20$ GeV, $M_{\eta_\pm} = 1$ TeV. [Right]: Parameter space for scotogenic model in the plane of N_1 Yukawa and its mass consistent with SIDM relic.

Summary and Conclusion

- We studied velocity dependent self-interacting DM with a light mediator as a possible resolution to the small scale anomalies associated with Λ CDM model.
- Thermal relic of SIDM is always under-abundant unless DM is at TeV scale, however higher masses are disfavoured from direct search even for very small kinetic mixing $\epsilon \sim 10^{-9}$.
- A hybrid set up of dark freeze-out and freeze-in is necessary to obtain the correct relic, which often needs extra particles which can decay to dark matter at a late time.
- We have also explored possible connection to the neutrino phenomenology in two different models.
- Future data from direct search experiments and complementary astrophysical searches will be able to further constrain such scenario.



*Sincerely,
Manoranjan*